Development of Microclimate Personal Cooling System Based on Thermoelectric Effect

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Abstract*— This article investigates the effect of a thermoelectric assisted water cooling method for the regulation of core body temperature of workers exposed to high temperature environments. The global objective for this microclimate personal cooling system is to establish a stable core body temperature and enhance performance of individuals in long time exposure to environments of extreme heat. This article contains determination of the heat load required to remove to keep the core body temperature of individual working in specified working conditions through calculation and data collection, design a thermoelectric cooling (TEC) system that can meet the calculated load considering design parameters of thermoelectric coolers, Provide experimental and software analysis of various components and working of whole system. Analysis involves CFD analysis of flow through tubing for the software confirmation of calculated values. The proposed cooling vest with its low cost, weight, and power consumption makes itself an excellent alternative where conventional air conditioning systems fails.

Keywords*— Thermoelectric module, Thermoelectric cooling vest, Heat stress, Peltier effect, Heat transfer.

INTRODUCTION

There are many situations where conventional air conditioning systems fails. Workers exposed to harsh environment are likely to have heat stress. Providing a microclimate system for personal cooling is the only option in those situations. This article focuses on developing a microclimate cooling system in the form of a cooling vest works on the principle of Peltier effect.

The human body maintains a fairly constant core temperature, primarily through varying the rate and amount of blood circulation through the skin and the release of fluid onto the skin by the sweat glands. Hot working conditions demand a stable core body temperature. If a person is failed to achieve a stable condition it affects adversely the peak performance of him/her, and also possess detrimental health effects such as heat stroke/stress, cramps, fainting, and breakdown of central nervous system when core body temperature reaches above 41.5˚C.

Objective of this research is to demonstrate the proposed cooling system can assist to maintain stable core body temperature of individuals working in extreme harsh environments. This is achieved by maintaining a constant skin temperature of 35˚C. A thermoelectric cooler maintains temperature of water at 21 ˚C so that when it is pumped through cooling tubes can take a heat load of 206 W in order to maintain body temperature to desired levels.

The critical body temperature for peak performance is between 38.33˚C and 39˚C as stated in [1]. This temperature represents heat stress for situations that are not encountered for prolonged time periods. The benefit of a cooling system would be to prevent the individuals from reaching this point, by maintaining the core body temperature at a lower safe temperature; one that is maintained by the body. This vest will be designed to reduce or eliminate the detrimental effects of heat stress and strain.

Heat strain reaches a very dangerous level at a body temperature of 40˚C. This temperature is accepted as the onset temperature where a human is in impending danger of irreversible heat stroke [1]. The atmospheric temperature alone is dangerous to the human body, but, coupled with long periods of exercise, a fatal situation can result. The human body itself generates heat due to its metabolic procedures; heat is gained as well from the environment.

I. DESIGN APPROACH

The following methodology is adopted in this article for the design of thermoelectric assisted microclimate cooling system. Work includes designing a torso region microclimate cooling vest to provide the necessary cooling for the worker.

- Problem definition
- Heat load calculations
- Design of vest and cooling systems
- Material and system selection
- Software and experimental analysis

A. *Problem Definition*

Considering a person working in harsh working conditions of 48˚C and low relative humidity 9-11% RH [3]. Personal cooling system needed to keep skin temperature T_{sk} as 35˚C. This is to keep the core body temperature, T_{core} as 37˚C. Body temperature increasing beyond 41.5˚C causes heat stroke. An individual exposed to such elevated temperature for longer duration is likely to have his core temperature gradually increased.

Protective clothing minimizes the radiation heat stress on individuals and conduction. Convection heat transfer is also negligible because the clothing is tightly fitted on the worker, thus reducing the air flow space between the individual. The heat transfer from the environment heats up the clothing and thus the core body temperature will rise. Altering the microclimate around the individual with the help of cooling vest will provide a stable core body temperature within permissible limits.

B. *Heat Load Calculation*

Basic heat transfer mechanism governs the entire process in this article. The total heat stress developed in human body is the sum of metabolic heat generated in body, heat gained from environment and heat loss from body (which is negative) [1]. The same is expressed below,

Total Heat stress = heat generated in the body (metabolic heat) + heat gained from the environment (environmental heat)-heat loss from the body

NIOSH gives the basic heat balance equation,

$$\Delta S= (M-W) \pm C \pm R - E$$

Where ΔS is the change in body heat content, (M-W) is Total metabolism – external work performed, C is the convection heat exchange, R is the radiative heat exchange, E is the evaporative heat loss.

1) Convection: The rate of convective heat exchange is a function of the difference in temperature between the ambient air (T_a) and the mean weighted skin temperature (T_{sk}) and the rate of air movement over the skin (V_a).

$$C= 7.0\times V_a^{0.6}(T_a-T_{sk})= 7.0\times 0.2^{0.6}(48-35)=39.64 \text{ W}$$

Where C is the convective heat exchange, V_a is air velocity in meters per second.

2) Radiation: The radiative heat exchange is primarily a function of the temperature gradient between the mean radiant temperature of the surroundings (Tw) and the mean weighted skin temperature (Tsk). Radiant heat exchange is a function of the fourth power of absolute temperature of the solid surroundings less the skin temperature (Tw - Tsk) but an acceptable approximation for the customary one-layer clothed individual is

$$R= 6.6\times(Tw - Tsk) = 6.6\times(48-35)=85.8 \text{ Kcal/hr} =98.2 \text{ W}$$

Where R is the radiant heat exchange.

3) Evaporation: The evaporation of water (sweat) from the skin surface results in a heat loss from the body.The maximum evaporative capacity is a function of air motion (V_a) and the water vapor pressure difference between the ambient air (P_a) and the water vapor pressure difference between the ambient air (P_a) and the wetted skin at temperature (P_{sk}) the equation for this relationship is for the customary one layer clothed worker

$$E=2.4\times V_a^{0.6}\times(P_{sk}-P_a)= 14\times0.20.6\times(42.2-8.37) =206.37 \text{ W}$$

Where E is the evaporative heat loss

4) Metabolic Heat: This is the heat generated in the body due to metabolic activities. Exact calculation of this heat content will differ from person to person. Thus a standard procedure is followed here. Metabolic heat can be taken as 4 kcal/min for a 70 Kg male. This is the sum of 3 kcal/min for strenuous walking, 1 kcal/m in for using arms to carry machinery, and perform difficult tasks as stated in [1]. Metabolic heat, M=274.67 W

Total heat stress, $Q^{\cdot}$=M+C+R-E=274.67+39.64+98.2-206.37=206.14 W

Total heat stress is the heat load which has to be removed from the body to maintain the core body temperature to a constant value. External work has to be performed to nullify the effects of external heat loads. This work is obtained in the form of cooling effect from TEC.

C. *Heat Removal Calculations*

The heat load removal from the body is calculated as follows. For the water flowing through the copper tube, uniform heating is assumed to be provided to the flowing water by the body at elevated temperature of 45^0 c and the inlet temperature of water is 20^0 c [2]. Following simple heat transfer equations it can be found that outlet temperature of water is 21.5^0 c.

The Reynolds number is found as 9282.045. This implies that the flow is laminar. From the relation between Nusselt number and heat transfer coefficient, we can calculate the heat transfer coefficient value as 8043.1055 W/m^{2}K.

D. *Design of the Tube and Vest*

Based on the heat load calculations suitable vest material and tube can be selected. The water that is cooled in the system is circulated through the body through the tubes which are kept in contact with the body and stitched to the jacket. The material that must be used as the tube must be suitably selected that enables perfect heat transfer and sufficient flexibility

TABLE I
COMPARISON OF TUBE MATERIALS

Properties	**Tube material**		
	Copper	**Polyphenylene Sulfide (PPS)**	**Liquid Crystalline Polymer (LCP)**
Thermal conductivity	398 W/mK	20 W/mK	20W/mK
Density	8.96 g/cc	1.7 g/cc	1.84 g/cc
Advantages	Easily available in loose, High k value, Lower price	High flexibility	High flexibility
Disadvantages	Less flexibility	Available in bulk only, low K value	Available in bulk only, low K value

Table I shows copper is a potential tube material but offers less flexibility. Thermally conducting polymers provides better flexibility. This article investigates cooling effects when copper is used as the tube material.

Factors taken into consideration in choosing vest material are the cost and close fit for the wearer. It is preferable to have less material between the tube and body to improve heat conduction. This article suggests single layer clothing. Materials can be used are rexin and nylon blend or mesh fabric. Meshed fabric is preferred because of its air permeability and light weight property. Air permeability enables removal of heat by evaporative mode.

The vest should be light weight and comfortable. The vest has 2 layers. The layers are the outer shell of the vest, the inner mesh lining along with copper tubing pass in between. Each layer serves its own purpose in the vest. The outer shell of the jacket helped to protect the human torso from the harmful effects of the sun. The inner mesh lining provided a pathway allowing for tubing and a structural support.

E. *Thermoelectric Module Selection*

A TEC is a cooling/heating device based on Peltier - Seebeck effect. It can be considered a small heat pump that contains no moveable parts, which can be extremely advantageous. Inside is a heat flux created between the junctions of the two metals. Two wires are attached to one side of the TEC to allow for a power supply to run a current into the system. This transfer of heat from one side to the other is produced by the electric current that is supplied through the wires.

The main process that takes place in the jacket is that water is being circulated through the jacket through selected tubes, and the water absorbs heat from the body producing the cooling effect. This water then reaches the cylinder and the thermoelectric modules attached to the cylinder cool the water to initial condition.

The water reaching the cylinder after a circulation is usually at a high temperature almost equal to ambient temperature and this temperature is reduced to 21.50C with the help of thermoelectric modules attached to the cylinders. The heat to be removed from body to keep the body temperature at 200C is,

$$\dot{Q} = \dot{m}\,cp(Te-Ti) = 0.03317 * 4178 * 1.5 = 206.14 \text{ W}$$

TABLE II
THERMOELECTRIC MODULES AND THEIR SPECIFICATIONS

Product	**Imax (amps)**	**Vmax (volts)**	**Qmax (watts)**
TE-127-2.0-1.15	16.1	15.7	156
VT-199-1.4-0.8	11.3	24.6	172
HP-199-1.4-0.8	11.3	24.6	172
DRIFT 06	11.3	24.9	170

The above table II shows different thermoelectric modules which are available in market. When consider the requirement of 206.14 W to be removed, it is preferred to use Drift 06 thermoelectric module as the heat removing capability and also the physical parameter as mentioned in the table suits the need. Drift 06 is known as Deltron High Effective Single Stage Module Drift 06.

The properties of drift 06 are:

- The dimensions are usually 30 x 30mm to 48 x48mm
- The height ranges from 3.2mm to 4.1mm
- The cooling capacity 170 W
- The voltage needed is 24.9V
- The current it takes is 11.3A
- The temperature difference 69°C to 74°C

F. *Schematics of Cooling System*

The system consists of an aluminium cylinder on to which the thermoelectric modules are being attached in diametrically opposite sides. The figure 1 shows the CATIA model of the TEC assembly which matches our prototype TEC system. The one end of the tubing is attached to the top of the cylinder which is the return passage and the other end is attached to a pump which is drilled to the cylinder with no leakage of water.

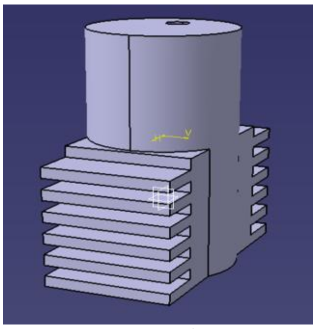

Fig. 1 CATIA model of TEC assembly

The cooling system consists of the thermoelectric system and the jacket. The thermoelectric system comprises of the thermoelectric modules, pump, fans and the tube is attached to the jacket, ends to the system. A schematic of the cooling system is shown in fig 3.

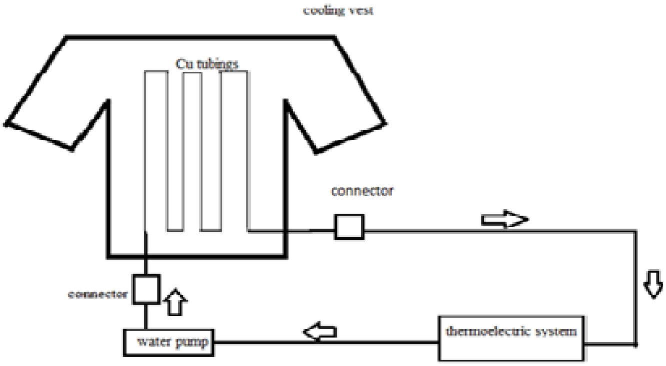

Fig. 2 Cooling System schematics

Water is mainly used in the system as the refrigerant. The water which is cooled in the cylinder using the thermoelectric modules is pumped through the tube using a pump. The one end of the tube is attached to the pump and the other end on the top of the cylinder through which water circulates back to the cylinder.

When water flows through the tubes it absorbs heat from the body and temperature of water increases and this water flows back into the cylinder which is cooled using the thermoelectric modules. Thus the cooling effect takes place and the body temperature gets reduced. Heat load calculations are done in order to calculate the amount of water needed and the thermoelectric cooling module.

II. Analysis and Results

Software analysis using ANSYS CFD is carried for the verification of the calculated heat load values. This software analysis also provides a data base for future systems considering different load conditions. Experimental analysis are carried out in a prototype.

A. *Software Analysis*

Software analysis of the tube flow was carried out using ANSYS software. The main objective of ANSYS analysis was the software confirmation of heat load calculation and to obtain a data base so that further studies can be carried out on the basis of this. CFD model of tube flow is illustrated below. ANSYS CFD software is used for the simulation of flow through tubing and heat transfer.

Geometry for the analysis is generated using CATIA with following dimensions,

- Length = 6 m
- Internal diameter = 5.7 mm
- Outer diameter = 6 mm

Based on thermodynamic and heat transfer principle, the input parameters required to carry out the analysis are the inlet velocity and temperature. From discharge calculations the velocity is calculated. Inlet temperature is set to a constant value based on the TEC characteristics.

- Inlet velocity = 1.3 m/s
- Inlet temperature = 303 K
- Flow type = laminar

Water flowing through the tubing is constantly under a heat load generated by body which accounts for the heat gained from environment as well as the heat generated due to metabolic activities. From NIOSH data this heat load is calculated as 206 W, i.e, surface heat load 206 W.

Following results are obtained from the software analysis.

1) Outlet temperature = 304 K: The outlet temperature obtained from CFD analysis is close to calculated value 304.5 K. Contours of temperature is shown below in fig. 3.

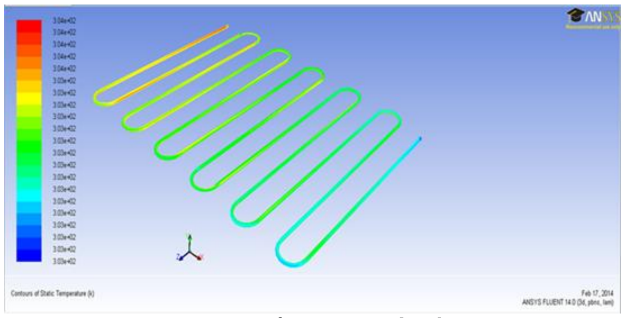
Fig. 3 Contours of temperature distribution

2) Mass flow = 0.033 Kg/s:

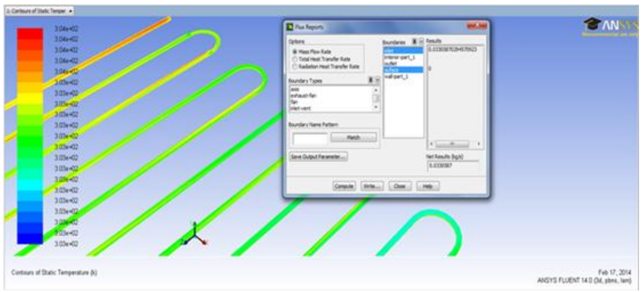
Fig. 4 Contours of mass flow rate

Contours of mass flow rate is shown in fig. 4.

3) Velocity contours: Velocity contours shown in fig. 5 does not show much variations and are within limits. The DC motor pump is capable to pump the water with sufficient velocities to facilitate the heat transfer while the water comes in contact with skin.

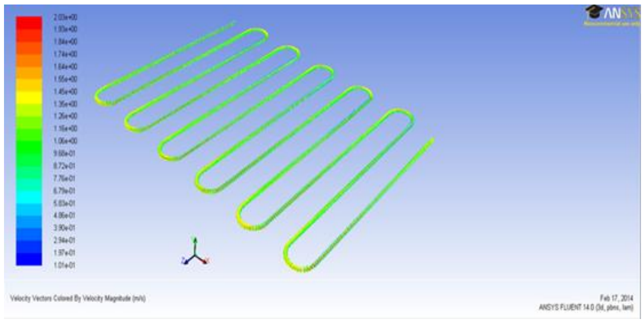
Fig. 5 Contours of velocity

B. *Experimental Results*

When experiments were done on the prototype made, the cooling rates were noted at different conditions and the table 3 shows it.

TABLE III
RESULTS OF EXPERIMENTAL READINGS

Time Taken(Min)	Temperature Obtained (^{0}c)	
	Using Single Module	Using Merged Module
Initially	30	30
10	28	25
15	26	22
20	24	19
25	21	17
30	19	15

Experimental results shown in table III are obtained by monitoring the system against the pre-established time scale. Readings are taken with the help of a digital thermo meter. Cooling rate readings of single and merged modules are compared against each other in the same time scale.

Thus it was found that when merged thermoelectric modules were used the cooling rates have increased considerably. The fabrication process involved trial and error use of thermoelectric modules in merged and unmerged conditions under various conditions. Merged modules always provides higher heat removal rate. This will allow TEC to be made from a number of small power modules. This will in turn reduce the power consumption and the weight of the assembly. Power consumption and weight are the two governing parameters in the selection of microclimate cooling system. Thus the proposed thermo electric cooling system is a potential candidate in personal cooling systems.

III. CONCLUSIONS

The work carried out indicates that thermoelectric cooling is a viable solution for controlling body core temperature for individuals working in harsh environment. The experimental data shows that use of more number of TEC modules increases the rate of cooling.

As first phase a vest was designed considering the actual situation and determined the design value. The value derived was verified using CFD software and was found correct.

In the second phase the designed system was manufactured, in which copper tubes are used instead of polymer and a combination of two TEC modules are used. By carrying out experiments on the prototype it is revealed that the prototype is effective in lowering the temperature and the cooling rate is increased by using merged modules. Considering the weight and power requirements, the thermoelectric based microclimate cooling vest is an effective alternative.

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